

# Gauge Mediation in String Theory

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## Abstract

We show that a large class of phenomenologically viable models for gauge mediation of supersymmetry breaking based on meta-stable vacua can be realized in local Calabi-Yau compactifications of string theory.

## 1. Introduction

The use of meta-stable vacua in supersymmetric model building has attracted much attention lately, especially after the discovery [1] that generic supersymmetric field theories in four dimensions such as the supersymmetric QCD with massive flavors have meta-stable vacua with broken supersymmetry. In [2], realistic models of direct mediation were constructed using superpotentials without  $U(1)_R$  symmetry. Though explicit breaking of the  $U(1)_R$  symmetry generates meta-stable vacua, there is a range of parameters where one can make them sufficiently long lived, while satisfying the phenomenological constraints on the masses of the gauginos, the gravitino, and the scalars without artificially elaborate constructions. The models can also avoid producing Landau poles in standard model gauge interactions below the unification scale. Recently beautiful realizations of these models in string theory, including a natural mechanism to generate small parameters of these models, were found in [3].

Gauge mediation models were also constructed using meta-stable vacua with similar phenomenological benefits [4,5]. Related ideas have been explored in [6-10]. Accepting the possibility that our universe may be in a meta-stable state allows us to circumvent the theoretical constraints due to the Nelson-Seiberg theorem on R-symmetry [11] and the Witten index [12] and gives us greater flexibility in model building, as emphasized in [13] among other recent papers.

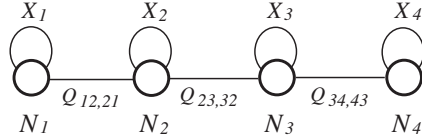
Among the models constructed recently based on meta-stable vacua, the ones discussed in [4] are particularly simple. In this paper, we will show that they have ultra-violet completions in supersymmetric quiver gauge theories which can be realized in string compactifications. Moreover, our construction can be naturally generalized to a large class of quiver gauge theories, providing a basis for the speculation in [4] that “gauge mediation may be a rather generic phenomenon in the landscape of possible supersymmetric theories.” In this paper, we will demonstrate the idea by explicitly working out one example: a model based on type IIB superstrings compactified on the  $A_4$ -fibered geometry [14]. We will also give an outline of generalizations of this construction to a large class of quiver gauge theories. Detailed analysis of meta-stable vacua in these models will be given in a separate paper [15].

## 2. The Model

The model we will consider in this paper is realized in string theory compactified on the local Calabi-Yau manifold described by the equation,

$$\begin{aligned} x^2 + y^2 + \prod_{i=1}^5 (z + t_i(w)) &= 0, & \sum_{i=1}^5 t_i(w) &= 0, \\ t_i(w) - t_{i+1}(w) &= \mu_i(w - x_i), & (x, y, z, w) &\in \mathbb{C}^4. \end{aligned} \quad (2.1)$$

Since  $t_i$ 's are functions of  $w$ , this gives the  $A_4$  singularity fibered over  $w \in \mathbb{C}$ . In particular, there exist four two-cycles  $S^2$  on which D branes can be wrapped. The low energy limit of D5 branes wrapping the two-cycles  $S^2$  and extending along the four uncompactified dimensions is the  $A_4$  quiver gauge theory with the gauge group  $U(N_1) \times U(N_2) \times U(N_3) \times U(N_4)$  with the adjoint chiral multiplets  $X_{i=1,2,3,4}$  for the four gauge group factors and the bi-fundamental chiral multiplets  $(Q_{12}, Q_{21})$ ,  $(Q_{23}, Q_{32})$ , and  $(Q_{34}, Q_{43})$ . This quiver gauge theory can also be realized on intersecting brane configuration with NS5 and D4 branes, as expected from the T-duality between the  $A_n$  singularity and NS5 branes [16].



**Fig. 1:**  $A_4$  quiver diagram

From the Calabi-Yau singularity (2.1), one can read off the superpotential of the quiver theory as [17,18]

$$W_{A_4} = \sum_{i=1}^3 \text{tr} (Q_{i+1,i} X_i Q_{i,i+1} - Q_{i,i+1} X_{i+1} Q_{i+1,i}) + \sum_{i=1}^4 \text{tr} \frac{\mu_i}{2} (X_i - x_i)^2. \quad (2.2)$$

Note that the dimensionful parameters  $\mu_i$  and  $x_i$  are the moduli of the Calabi-Yau manifold given by (2.1), namely they are closed string moduli. The dynamical scales  $\Lambda_{i=1,\dots,4}$  of the four gauge group factors are also closed string moduli, related to the sizes of the  $S^2$ 's. These closed string moduli are frozen and can be regarded as parameters of the low energy theory. Let us suppose that  $\mu_i$  are sufficiently larger than  $\Lambda_i$  so that we can integrate out all the adjoints  $X_i$  to obtain the effective superpotential

$$\begin{aligned} W_{\text{eff}} &= \sum_{i=1}^3 m_i \text{tr} Q_{i+1,i} Q_{i,i+1} - \sum_{i=1}^3 \frac{1}{\tilde{\mu}_i} \text{tr} (Q_{i+1,i} Q_{i,i+1})^2 \\ &\quad + \frac{1}{\mu_2} \text{tr} Q_{21} Q_{12} Q_{23} Q_{32} + \frac{1}{\mu_3} \text{tr} Q_{32} Q_{23} Q_{34} Q_{43}, \end{aligned} \quad (2.3)$$

where

$$m_i = c_i - c_{i+1}, \quad \tilde{\mu}_i = \frac{2\mu_i\mu_{i+1}}{\mu_i + \mu_{i+1}} \quad (i = 1, 2, 3).$$

This quiver gauge theory can be used as a gauge mediation model as follows. We identify the bi-fundamentals  $(Q_{34}, Q_{43})$  as messenger fields. One way to incorporate the standard model sector would be to identify a subgroup of the  $U(N_4)$  gauge group with the standard model gauge group or a GUT gauge group. Alternatively, we can replace the 4th node of the quiver diagram of Fig. 1 carrying the  $U(N_4)$  gauge group with a string theory construction of the standard model. For example, if the standard model is realized on intersecting branes, messengers can be open strings connecting the 3rd node carrying the  $U(N_3)$  gauge group to the standard model branes.<sup>1</sup> In the following, we will denote the bi-fundamental fields  $(Q_{34}, Q_{43})$  as  $(f, \tilde{f})$  to distinguish them from the rest of the quiver gauge theory and to emphasize their role as the messengers.

The rest of the quiver gauge theory is treated as a hidden sector, where supersymmetry is broken dynamically. To use the result of [1], let us assume that the ranks of the gauge group factors satisfy

$$N_2 + 1 \leq N_1 + N_3 < \frac{3}{2}N_2 \quad (2.4)$$

and that

$$\Lambda_1, \Lambda_3, \Lambda_4 \ll \Lambda_2 \ll \mu_i.$$

In this case, one can identify the gauge group  $SU(N_c)$  of the model of [1] with  $SU(N_2) \subset U(N_2)$  of the quiver theory. Since the metastable vacuum can be found near the origin of the meson fields  $M_{11} \sim Q_{12}Q_{21}$ ,  $M_{33} \sim Q_{32}Q_{23}$ , the terms  $\text{tr}(Q_{12}Q_{21})^2$ ,  $\text{tr}(Q_{32}Q_{23})^2$  and  $\text{tr}(Q_{12}Q_{21}Q_{32}Q_{23})$  in the superpotential (2.3) are irrelevant in our discussion below, if the masses  $\mu_i$  of the adjoints satisfy the following bounds [4,5],

$$\frac{\Lambda_2^2}{\tilde{\mu}_{1,2}}, \frac{\Lambda_2^2}{\mu_2} \leq \min \left\{ \frac{1}{4\pi} \sqrt{m_{1,2}\Lambda_2}, \frac{1}{16\pi^2} \frac{m_3\mu_3}{\Lambda_2} \right\}. \quad (2.5)$$

In this range of the parameters, the hidden sector and its interaction with the messenger sector is described by the superpotential,

$$W = m \text{tr} Q_{12}Q_{21} + m \text{tr} Q_{32}Q_{23} + \frac{1}{\mu_3} \text{tr} Q_{32}Q_{23}f\tilde{f} + m_3 \text{tr} f\tilde{f} - \frac{1}{\tilde{\mu}_3} \text{tr} (f\tilde{f})^2. \quad (2.6)$$

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<sup>1</sup> In this case, we can still use the effective potential (2.3) to describe the interaction of the messengers and the hidden sector, but we should set  $1/\tilde{\mu}_4 = 1/(2\mu_3)$  since we do not have the adjoint field  $X_4$ .

Here, we set the mass parameters  $m_1 = m_2 = m$ , for simplicity. Consider the case when  $N_1 = N_2 = 3$  and  $N_3 = 1$  so that the Landau pole problem can easily be avoided. The resulting model is a variant of the models proposed in [4]. The model [4] has the global symmetry  $U(4) \times U(1)_{\text{mess}}$ , where  $U(4)$  is the flavor symmetry of the ISS model and  $U(1)_{\text{mess}}$  acts on the messengers  $(f, \tilde{f})$ . The meta-stable vacuum spontaneously breaks the  $U(4)$  symmetry, giving rise to Nambu-Goldstone bosons, when  $m_1 \simeq m_2$ . In our model, the would-be Nambu-Goldstone bosons are eaten by the gauge symmetry. This difference is not important in the low energy analysis of supersymmetry breaking effects.

Let us discuss phenomenological constraints on the parameters in (2.6). We will focus on the following part of the superpotential (2.6),

$$W_{\text{mess}} = \frac{\Lambda_2}{\mu_3} M_{33} f \tilde{f} + m_3 f \tilde{f}, \quad (2.7)$$

where  $M_{33} = Q_{32}Q_{23}/\Lambda_2$  is neutral under the  $U(N_3) = U(1)$  gauge group. We have dropped the irrelevant quartic term  $(f\tilde{f})^2$  because the messengers  $(f, \tilde{f})$  are weakly interacting at energies above the electroweak scale, if the mass parameter  $\tilde{\mu}_3$  is large enough. The  $F$ -component of the meson superfield  $M_{33}$  develops the vacuum expectation value and breaks supersymmetry [1]. The supersymmetric mass and the soft supersymmetry breaking mass of the messenger fields  $(f, \tilde{f})$  are then given by

$$W_{\text{mess}} \simeq \left( m_3 + \theta^2 \frac{m\Lambda_2^2}{\mu_3} \right) f \tilde{f}. \quad (2.8)$$

Following the analysis in [4,5], we find that all the phenomenological requirements for the messenger sector can be satisfied, for example, in the following range of parameters,

$$\begin{aligned} \Lambda_2 &\simeq 10^{11} \text{GeV}, \quad m \simeq 10^8 \text{GeV}, \quad m_3 \simeq 10^7 \text{GeV}, \\ \mu_1 &\geq \mu_2 \geq 10^{13} \text{GeV}, \quad \mu_3 \simeq 10^{18} \text{GeV}. \end{aligned} \quad (2.9)$$

### 3. Generalization

We found that both the messenger sector and the hidden sector of the models proposed in [4] can be realized in the  $A_4$  quiver gauge theory. This construction naturally suggests the following generalization. Consider a quiver diagram which can be separated into two disjoint diagrams  $\Gamma_1$  and  $\Gamma_2$  by cutting at one node, which we denote by  $a$ . If the scale  $\Lambda_a$  associated to the gauge group on the  $a$ -node is sufficiently low, and if superpotential

interactions between them are small, we have effectively two separate quiver gauge theories for phenomena much above the scale  $\Lambda_a$ , one associated to  $\Gamma_1$  and another associated to  $\Gamma_2$ , which are weakly interacting with each other through the  $a$ -node. If supersymmetry is broken in the sector  $\Gamma_1$ , it can be communicated to the sector  $\Gamma_2$  by the gauge mediation mechanism. The beauty of the quiver gauge theory construction is that, because of the presence of bi-fundamental and adjoint fields on links and nodes, an effective superpotential of the form (2.8) is naturally generated when supersymmetry is broken in a part of the diagram connected to the  $a$ -node.

It follows trivially that any quiver theory that is vector like with adjustable mass terms has meta-stable supersymmetry breaking vacua in some range of its parameter. All one has to do is to identify a part of the diagram where supersymmetry can be broken using a known mechanism, for example as in [1] or its variant [19], and to have its effect communicated to the rest of the diagram by messengers. One can also consider the scenario where the quiver theory associated to a sub-diagram  $\Gamma_2$  has a supersymmetric vacuum with dynamically generated small scales, which can be used to set parameters of the theory associated to another sub-diagram  $\Gamma_1$ , where supersymmetry is broken. The supersymmetry breaking effect can then be communicated back to the sub-diagram  $\Gamma_2$ . This would give a string theory realization of the idea of [20]. These and other mechanisms of supersymmetry breaking will be explored further in [15].

These supersymmetry breaking quiver gauge theories can be coupled to the messenger sector. In fact, as in the case of the  $A_4$  model discussed in the previous section, the messenger sector itself can be included in quiver theories. If the messenger sector is attached at the end of the quiver diagram, the effective low energy superpotential always takes the form (2.3). Thus, one can see that the models in [4] and their generalizations are robust and naturally appear in this large class of string compactifications.

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